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Determining the Physical Properties of Very-Low-Mass Stars and Brown Dwarfs in the Near-Infrared[1]

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Abstract. Accurate measurements of the fundamental physical properties of very-low-mass stars and brown dwarfs are crucial for calibrating evolutionary models. Photometry and low-resolution spectroscopy effectively average over absorption features that sample different layers in complex cool atmospheres. By studying a large sample of objects bright enough for high-resolution spectroscopy, we can develop methods for determining physical properties as accurately and efficiently as possible. As part of the Brown Dwarf Spectroscopic Survey (BDSS; [1, 2]), we are conducting a detailed comparison of observed and synthetic spectra for a sample of young M and L dwarfs and field M, L, and T dwarfs ($\sim$50 objects in total). High-resolution near-infrared spectra from NIRSPEC on Keck II provide an unequaled combination of resolving power and wavelength coverage. Synthetic spectra were created from `PHOENIX` atmosphere models calculated exclusively for this project with updated line lists and solar abundances. Combined with spectral types from photometric studies and low-resolution spectra and surface gravity estimates from age determination, the high-resolution spectra enable precise measurements of effective temperature and surface gravity, as well as accurate determination of radial velocity and projected rotational velocity. Our preliminary observation-model comparisons distinguish between wavelength regimes for which the models reproduce observed high-resolution spectra and regimes in which model data (line lists, oscillator strengths, etc.) are lacking.

Keywords: Stars: low-mass, brown dwarfs, Stars: atmospheres, Infrared: stars, Techniques: spectroscopic
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1. INTRODUCTION

As the lowest mass and likely most common star-like objects in the Galaxy, it is important to understand the physical properties, formation, and evolution of brown dwarfs in order to fully characterize the low end of the initial mass function and the mass dependence of various processes in star formation. Brown dwarf atmospheres are crucial links between the low-mass stars and Solar System planets we can study in detail and

[1] The data presented herein were obtained at the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation.

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the extra-solar giant planets we cannot yet directly observe.

The cool, chemically complex atmospheres of brown dwarfs motivate the study of these intrinsically faint objects at high spectral resolution in the near-infrared. Photometry and low-resolution spectra effectively average over spectral features which may sample different parts of the atmospheric structure and untangle degeneracy between physical parameters with similar effects on spectral features. Observing in the near-infrared, where the spectral energy distributions of brown dwarfs peak, provides a wealth of resolved atomic and molecular lines for detailed study. This is especially important for the study of low-mass objects because their spectra contain increasingly numerous and blended lines as effective temperature decreases.

2. SAMPLE & OBSERVATIONS

In order to explore the dependence of spectral features on atmospheric properties over the broadest possible parameter space, our sample contains a large number and variety of objects. We have so far observed over 50 M, L, and T dwarfs with ages ranging from $\sim$1 Myr to $\geq$1 Gyr. The young objects are mainly M dwarfs with known membership in near-by star-forming regions (e.g. Taurus, ρ Ophiuchi, and Upper Scorpius; ages $\sim 1-10$ Myr) or moving groups (e.g. TW Hydrae; ages $\geq$10 Myr). The stellar-substellar mass boundary is expected to lie around a spectral type of M6-M6.5 for brown dwarfs younger than $\sim$100 Myr [3]. This project will concentrate on late M and early L dwarfs for which simplified dust treatments are sufficient to reproduce observed colors [4, 5, 6, 7].

High-resolution *J*-band spectra were obtained with the NIRSPEC cross-dispersed echelle spectrometer on the Keck II telescope. With the instrumental settings described in [1], spectral coverage is nearly complete from 1.165 to 1.324 μm. The reduced data contains eight spectral orders, 58 to 65, at a resolving power of R$\sim$20,000. The majority of the objects in our sample were also observed at medium resolution (R$\sim$2,000) with NIRSPEC for previous BDSS projects. For further details about observations and data reduction, see [1]. These spectra will be added to the BDSS Public Archive[2] upon completion of this project.

3. MODEL ATMOSPHERES

We calculate atmospheric structures (Figure 1, left) and high-resolution spectra using version 15 of the `PHOENIX` model atmosphere code [8, 9]. We use the DUSTY version of the code so that single-species dust is created in chemical equilibrium conditions and remains as an opacity course where it is formed [7]. This is a limiting case of dust treatment that ignores nucleation, grain growth, sedimentation and convective upwelling and leads to very dusty atmospheres. However, the DUSTY models have been shown to provide reasonable fidelity to observational properties of late-M and early-L

[2] http://www.astro.ucla.edu/~mclean/BDSSarchive/

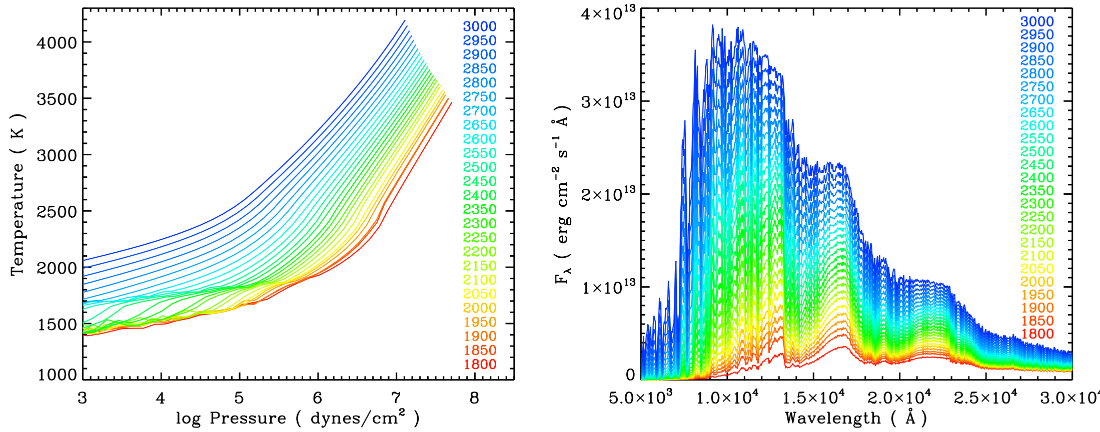

FIGURE 1. Left: Temperature-pressure profiles of model atmosphere structures calculated using the `PHOENIX` code. The surface gravity is log(g)=5.0, a typical value for field brown dwarfs. Right: Spectral energy distribution for the same model atmospheres.

dwarfs and as such, are suitable for our initial sample [7]. All models are calculated at solar metallicity.

We incorporated updated molecular line lists (FeH: [10], CrH: [11], H_2O: [12]) and solar abundances [13] to calculate structures in 50 K intervals in effective temperature (T_{eff}) from 1800 to 3000 K and in 0.1 dex intervals of surface gravity (log[g]) from 3.0 to 6.0. All of these structures are converged in that the emergent flux calculated by integrating under the spectral energy distribution is within 5% of the prescribed flux, $\sigma\ T_{eff}^4$ (Fig. 1, right). High resolution spectra are calculated using these temperature-pressure structures at 0.3Å resolution from 1.1 to 2.5 μm. This spectral resolution over-samples the effective resolving power of NIRSPEC in the *J* band by a factor of two.

4. COMPARISON OF OBSERVED AND MODEL SPECTRA

We compare observed spectra to synthetic spectra with expected physical parameters based on spectral type and age for a sub-set of objects. In NIRSPEC dispersion order 65 the dominant features are K I lines that become increasingly pressure-broadened with decreasing temperature and increasing surface gravity. In Figure 2, observed order 65 spectra (left) are shown alongside synthetic spectra (right) at the typical surface gravity for field dwarfs (log[g]=5.0) and the range of effective temperatures that is expected for these spectral types, e.g. [14]. The synthetic spectra appear to reproduce the broadening of the K I lines (marked by dot-dashed vertical lines) at later spectral types with cooler effective temperatures. Several weaker spectral features and their temperature dependence are also reproduced by the models.

We use two statistical fitting techniques, Levenberg-Marquardt least-squares minimization and Markov chain Monte Carlo to determine best-fit model parameters for observed spectra and estimate uncertainties in those parameters. Both fitting methods are provided with a linear interpolation procedure so that model parameters are selected

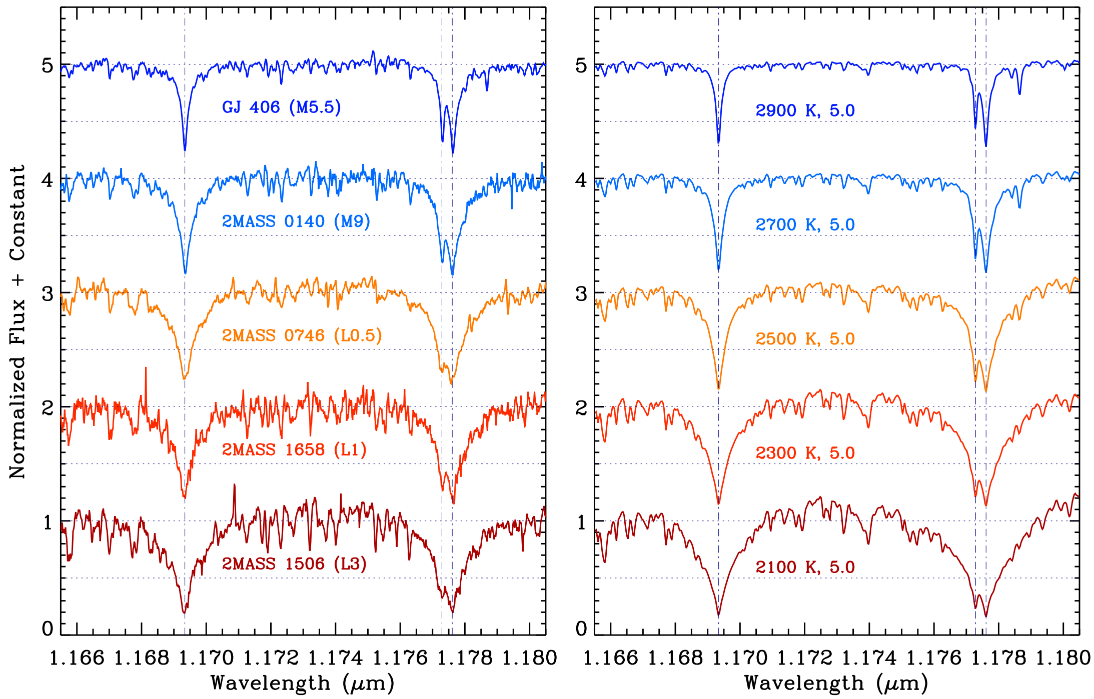

FIGURE 2. Spectral type sequence of order 65 NIRSPEC spectra (left) and effective temperature sequence of synthetic spectra (right). K I lines are marked with dot-dashed vertical lines, and dotted horizontal lines show vertical offsets. These are not best fits, but rather a sample of expected effective temperatures.

from an effectively continuous grid of models within the range of parameters. High-resolution spectra have radial velocity and projected rotational velocity as free parameters, in addition to effective temperature and surface gravity that are parameters for medium-resolution fits.

5. ANALYSIS & CONCLUSIONS

Medium-resolution spectra of two M dwarfs, one field (high surface gravity) and one young (low surface gravity) along with best-fit synthetic spectra are shown in Figure 3. As expected, the earlier-type field objects is best fit by a slightly higher effective temperature (2980 K vs. 2870 K) and higher surface gravity (log[g]=5.45 versus 3.95) than the young dwarf. The continuum slope and strong spectral features are well-matched by the synthetic spectra, but there are some apparent mis-matches as well.

In Figure 4, high-resolution spectra are plotted with best-fit model parameters from the medium-resolution fit, along with appropriate velocity parameters. For the field M dwarf GJ 406, the parameters from the medium-resolution model fit replicate the pressure-broadened atomic lines in order 65, but the strengths of the molecular lines in order 62 are under-predicted by the model. Whereas, for the lower gravity object GY 5,

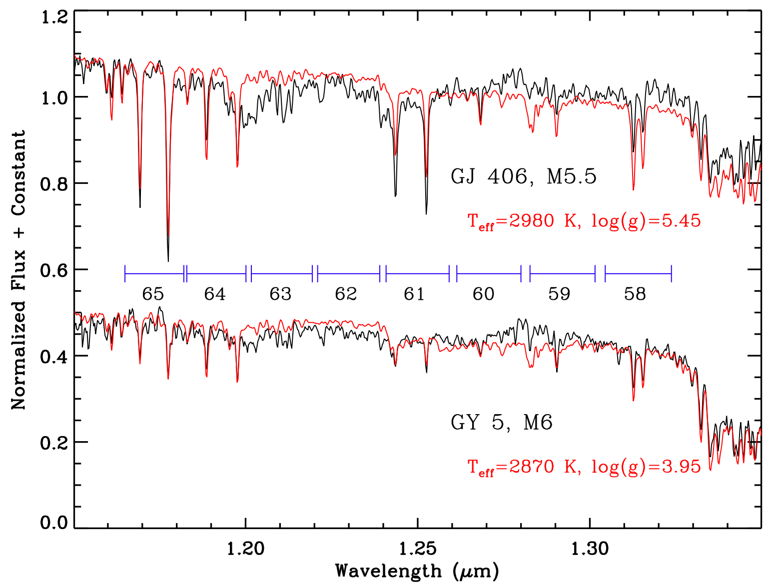

FIGURE 3. Medium-resolution *J*-band spectra of field (old) M dwarf GJ 406 and young M dwarf GY 5, a member of the ρ Ophiuchi star-forming region and best-fit synthetic spectra. Barred horizontal lines denote the wavelength coverage of NIRSPEC echelle orders.

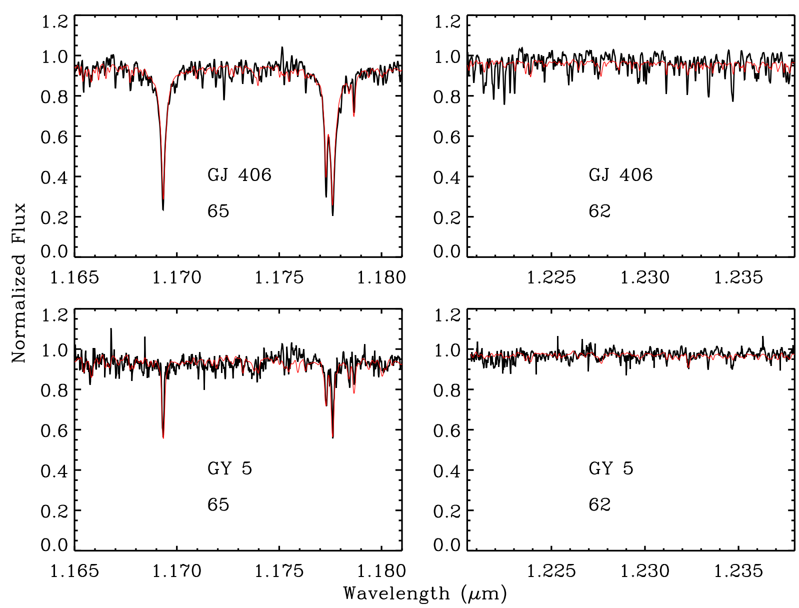

FIGURE 4. High-resolution spectra and model fits for GJ 406 (top) and GY 5 (bottom), NIRSPEC orders 65 (left) and 62 (right). The model parameters for T_{eff} and log(g) are the same as in fig. 3. Radial and projected rotational velocities are +20 km s^{-1} and 10 km s^{-1} for GJ 406 and -4 km s^{-1} and 20 km s^{-1} for GY 5, respectively.

the model fits are not quite as good for the strong atomic lines, but are better for the weak molecular lines. Radial velocity is measured with a precision of about 1 km s^{-1} for both objects. Projected rotational velocity is not yet well-determined by the fitting routines but can certainly be measured from NIRSPEC spectra with a precision of at least 5 km s^{-1}.

In summary, this work presents preliminary results from a project at the intersection between a unique observational dataset and state-of-the-art atmosphere models. Comparisons of these data at high spectral resolution will allow the determination of physical properties for a variety of very-low-mass stars and brown dwarfs as well as the identification of deficiencies in the models.

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